

Switching Regulators for Poets A Gentle Guide for the Trepidatious

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The above title is not happenstance and was arrived at after considerable deliberation. As a linear IC manufacturer, it is our goal to encourage users to design and build switching regulators. A problem is that while everyone agrees that *working* switching regulators are a good thing, everyone also agrees that they are difficult to get working. Switching regulators, with their high efficiency and small size, are increasingly desirable as overall package sizes shrink. Unfortunately, switching regulators are also one of the most difficult linear circuits to design. Mysterious modes, sudden, seemingly inexplicable failures, peculiar regulation characteristics and just plain explosions are common occurrences. Diodes conduct the wrong way. Things get hot that shouldn't. Capacitors act like resistors, fuses don't blow and transistors do. The output is at ground, and the ground terminal shows volts of noise.

Added to this poisonous brew is the regulator's feedback loop, sampled in nature and replete with uncertain phase shifts. Everything, of course, varies with line and load conditions—and the time of day, or so it seems. In the face of such menace, what are Everyman and the poets to do?

The classic approach is to seek wisdom. Substantial expertise exists but is concentrated in a small number of corporate and academic areas. These resources are not readily accessed by Everyman and some cynics might suggest that they are deliberately protected by a self-

serving priesthood. A glance through conference proceedings and published literature yields either a storm of mathematics or absurdly coy and simple little block diagrams that make everything look just so easy. Either way, Everyman loses. And the poets don't even get to try.

Something to think about is that most people who want switching regulators don't need 98.2% efficiency or 100W/cubic inch. They aren't trying to get tenure and don't care about inventing a new type of circuit. What they want are concepts directly applicable to construction of working circuits with readily-available parts. Thus equipped, Everyman can build and sell useful products, presumably buy more components and everyone's interests (not incidentally, including ours) are served.

As author, I must confess that I am more poet than switching regulator designer, and my poetry ain't very good. Before this effort, my enthusiasm level for switchers resided somewhere between trepidation and terror. This position has changed to one of cautiously respectful optimism. Several things aided this transformation and significantly influenced this publication. The "encouragement" of the Captains of this corporation, emphasized over the last year at increasingly insistent levels, constituted one form of inspiration. Conversations with users (or people who wanted to be) provided more valuable perspective and strength in the knowledge that I was not alone in my difficulties with switchers.

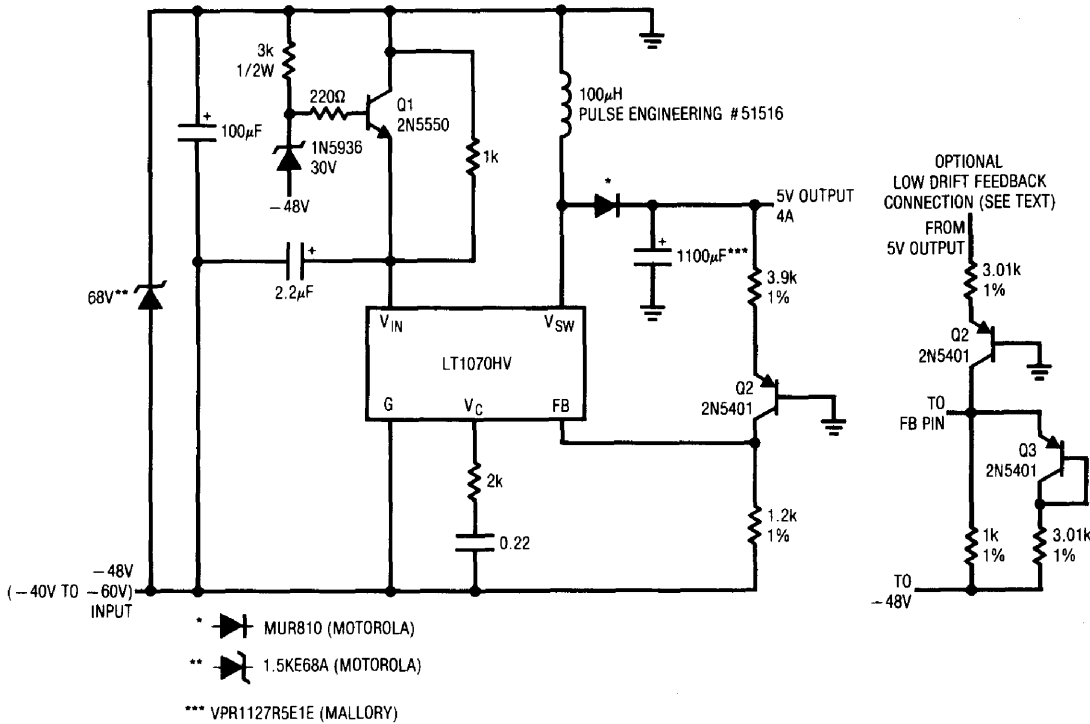


Figure 4. Non-Isolated -48V to 5V Regulator

Such mixing can promote poor regulation, unstable operation or outright oscillation. Similarly, the 22µF bypass capacitor ensures clean local power at the LT1070, even during the fast, high current drain periods when V_{SW} comes on. It should have good high frequency characteristics (tantalum or aluminum paralleled by a disc ceramic type). More discussion of these considerations appears in Appendix C.

-48V to 5V Telecom Flyback Regulator

Figure 4's circuit is operationally similar to Figure 1 but is intended for telecom applications. The raw telecom supply is nominally -48V but can vary from -40V to -60V. This range of voltages is acceptable to the V_{SW} pin but protection is required for the V_{IN} pin ($V_{MAX} = 60V$). Q1 and the 30V zener diode serve this purpose, dropping V_{IN} 's voltage to acceptable levels under all line conditions.

Here, the "top" of the inductor is at ground and the LT1070's ground pin at -48V. The feedback pin senses with respect to the ground pin, so a level shift is required from the 5V output. Q2 serves this purpose, introducing only -2mV/°C drift. This is normally not objectionable in a logic supply, but can be compensated with the optional appropriately scaled diode-resistor shown.

Frequency compensation is similar to Figure 1, although a low ESR (equivalent series resistance) capacitor gives less phase shift, permitting faster loop response with the reduced compensation time constant. The 68V zener is a type designed to clamp and absorb excessive line transients which might otherwise damage the LT1070 (V_{SW} maximum voltage is 75V).

Figure 5 shows operating waveforms at the V_{SW} pin. Trace A is the voltage and Trace B the current. Switching

If the inductor is enclosed in a feedback-enforced loop, such as Figure 1, the energy put into it will be controlled to meet circuit output demands. Figure 3 shows what happens when output demand doubles. In this case duty cycle doesn't change much but current doubles. This requires the inductor to store more energy. If it couldn't meet the storage requirement, e.g., it saturated and could not hold any more magnetic flux, it would cease to look inductive. If this point is reached, current flow is limited only by the resistance of the wire and rapidly builds to excessive and destructive values. This behavior is exactly the opposite of a capacitor, where current diminishes upon entering saturation. Capacitors can maintain energy storage with no current flowing; inductors cannot. See Appendix C, "A Checklist for Switching Regulator Designs," for details.

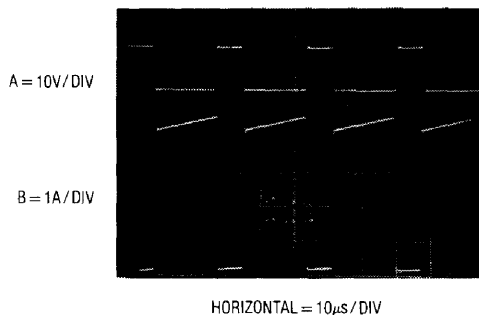


Figure 3. Flyback Regulator's Waveforms at 14W Loading

At the end of each inductor charge cycle, current flow in the inductor decays, and the magnetic field around it abruptly collapses. The V_{SW} pin is seen to rise rapidly to a voltage higher than the 5V input. This flyback action gives the regulator its voltage boost characteristics and its name. The boost characteristic is caused by the collapsing magnetic field's lines of flux cutting across the inductor's conductive wire turns. This satisfies the basic requirement for generation of a current in (and hence, a voltage across) a conductor. This moving magnetic field deposits energy into the wire in proportion to how much was stored in the core during the current charge cycle. It is worth noting that the operating characteristics shown here are similar to the Kettering ignition system used in automobiles, explaining why spark occurs when the points open.*

*Back when giants walked the earth, Real Cars used ignition points.

In this circuit the flyback is seen to clamp to a level just above the output voltage. This is so because the flyback pulse is steered through the Schottky diode to the output. The $470\mu\text{F}$ capacitor integrates the repetitive flyback events to DC, providing the circuit's output. The feedback pin (FB) samples this output via the 10.7k-1.24k divider. The LT1070 compares the feedback pin voltage to its internal 1.24V reference and controls the V_{SW} pin's duty cycle and current, closing a loop. Since the LT1070 is trying to force its feedback pin to 1.24V, output voltage may be set by varying the 10.7k or 1.24k values.

All feedback loops require some form of stability compensation (see the appended section of LTC Application Note AN-18, "The Oscillation Problem—Frequency Compensation Without Tears," for general discussion). The LT1070 is no exception. Its voltage gain characteristics, combined with the substantial phase shift of the circuit's sampled energy delivery, ensure oscillation if uncompensated. While the large output capacitor smooths the output to DC, it also teams up with the sampled energy coming into it to create phase shift. To complicate matters, the load, which may vary, also influences phase characteristics. The regulator can only source into the output capacitor. The load determines the sink time constant, influencing phase performance and overall stability.

The LT1070's internals have been designed with all this in mind and compensation is usually fairly simple. In this case the 1k-1 μF combination at the compensation pin (V_C) rolls off the circuit, providing stable compensation for all operating conditions (see Appendix B, "Frequency Compensation," for details and suggestions on achieving stability in switching regulator loops).

As innocent as Figure 1 appears, it's not too difficult to get into odd and seemingly inexplicable problems. Note that the ground connection appears at the ground pin, as opposed to its customary location at the bottom of the diagram. This is deliberate and the supply and load return connections should be made there. The high speed, high current returns from the output transistor's emitter (the "other end" of the V_{SW} pin) should not be allowed to mix with the small currents of the output divider or the V_C pin.

Application Note 25

At the circuit level, a significant decision was to employ standard, off-the-shelf magnetics exclusively.* This policy was driven by the observation that the majority of problems encountered with switchers centered around inductive components. This approach almost certainly prevents precisely-optimized performance and may horrify some veteran switcher designers. It also eliminates inductor construction uncertainties, saves time and greatly increases the likelihood of getting a design running. It's much easier to work with, and get enthusiastic about, a functional circuit than the smoking carcass of a devastated breadboard. If standard inductor characteristics aren't optimal, it's easier to see the evidence on a 'scope than to guess why you don't see anything.

Additionally, once the circuit is running, an optimized version of the standard product can be supplied by the inductor manufacturer. It's generally easier for the inductor manufacturer to modify its standard product than to start from scratch. The process of communicating and translating circuit performance requirements into inductor construction details is tricky. Using standard product as a starting point accelerates the dialogue, minimizing the number of iterations required for satisfactory results. Often, the standard product suffices for the purpose and no further effort is required.

Strictly speaking, it makes more sense to design the inductor to meet circuit requirements than to fashion a circuit around a standard inductor. Deliberately ignoring this consideration considerably complicated the author's work, but hopefully will simplify the reader's (such is the lot of an application note writer's life). Those interested in inductor design theory are commended to LTC Application Note AN-19, "LT1070 Design Manual."

*For recommended magnetics supplier, see page 13.

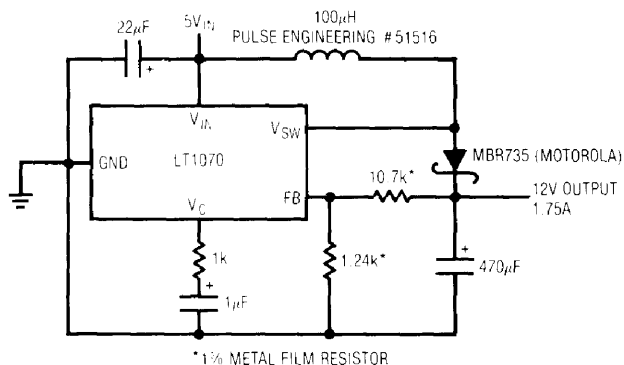


Figure 1. Flyback-Type Regulator

A final aid in achieving my new outlook on switchers was the LT1070 family. In terms of circuit construction and ease of use they really are superior switching regulator ICs. A 75V, 5A (LT1070HV) on-chip power switch, complete control loop, oscillator and only 5 pins eliminate a lot of the ambiguity of other devices. Internal details and operating features of the LT1070 family are detailed in Appendix A, "Physiology of the LT1070."

Basic Flyback Regulator

Figure 1 shows a basic flyback regulator using the LT1070. It converts a 5V input to a 12V output. Figure 2 shows the voltage (Trace A) and the current (Trace B) waveforms at the V_{SW} pin. The V_{SW} output is the collector of a common emitter NPN, so current flows when it is low. Current is pulled through the 100µH inductor and controlled to a value of which forces the 12V output to be constant. The circuit's 40kHz repetition rate is set by the LT1070's internal oscillator. During the time V_{SW} is low, current flow through the inductor causes a magnetic field to be induced into the area around the inductor. The amount of energy stored in this field is a function of the current level, how long current flows, the characteristics of the inductor and its core material. It is often useful to think of the inductor as a bucket and analogize current flow as water pouring into it. The ultimate limit on energy storage is set by the bucket's capacity, corresponding to the inductor's saturation limitations. The amount of energy that can be put into an inductor in a given time is limited by the applied voltage and the inductance. The amount of energy that can be stored without saturating the inductor is limited by the core characteristics. Size, core material, operating frequency, voltage and current influence inductor design.

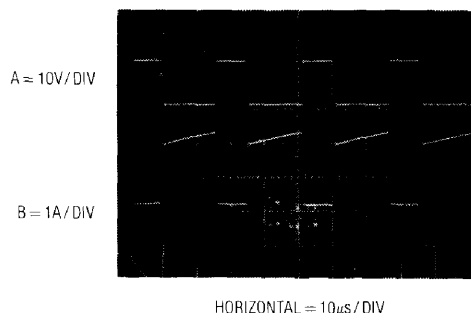


Figure 2. Flyback Regulator's Waveforms at 7W Loading

